The Intercomparison of Cloud Parameters Derived Using Multiple Satellite Instruments

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***Abstract*—Cloud optical thickness (COT) has been retrieved using multiple optical instruments onboard ENVISAT and compared for consistency for a single cloud field over central Europe. To match the spatial resolution of the Scanning Imaging Absorption Spectrometer for Atmospheric Chartography (SCIAMACHY), the results of retrievals from higher resolution instruments have been averaged on the scale of 30 × 60 km. It was found that the Medium Resolution Imaging Spectrometer (MERIS), Advanced Along Track Scanning Radiometer (AATSR), and SCIAMACHY (all onboard ENVISAT) give close values of COT and, therefore, cloud albedo. Similar results have been obtained for the Moderate Resolution Imaging Spectroradiometer onboard the Terra satellite. This suggests that these instruments can be used for synergetic retrievals of cloud properties from space. For instance, the high spectral resolution of SCIAMACHY can be used to enhance MERIS or AATSR retrievals of cloud top height and other cloud characteristics.**

***Index Terms*—Radiative transfer, remote sensing.**

I. Introduction

THE SCANNING Imaging Absorption Spectrometer for Atmospheric Chartography (SCIAMACHY) is a moderate resolution imaging spectrometer [2] onboard ENVISAT. The spectra are recorded simultaneously from 214–1750 nm and also in two smaller spectral regions 1940–2040 and 2265–2380 nm. Measurements of SCIAMACHY are performed in nadir, limb, and solar/lunar occultation modes (14 orbits per day); the scanwidth in nadir is 960 km, and the ground pixel size of SCIAMACHY varies with the spectral channels. Only pixels with a size of 30×60 km^2 have been used for cloud retrievals in this paper [7]. SCIAMACHY is designed for the accurate measurements of trace gases in the terrestrial atmosphere. Since clouds are present very often in the SCIAMACHY pixels, they are the main obstacles for a precise determination of gaseous concentrations from space [8]. Generally, there are two ways for trace gas abundance studies in the case of partially or completely cloudy pixels. First, one can reject these pixels and consider only cloudless situations. This leads to a great loss of data. Second, cloud properties can be incorporated in the retrieval scheme (e.g., cloud albedo, cloud altitude, and cloud fraction). Clearly, the second way is of an advantage as far as retrievals of atmospheric gases are concerned. A semianalytical cloud retrieval algorithm (SACURA) [7] has been developed specifically to provide necessary cloud information for the gaseous abundances retrievals. At the moment, SACURA is used at Bremen University in the ozone concentration retrieval scheme. This comprehensive cloud retrieval algorithm provides information on the cloud albedo, the cloud altitude, the cloud fraction, the cloud optical thickness (COT) at 0.44 μm, the cloud thermodynamic state, and the effective radius (ER) of particles are derived from the spectral top-of-atmosphere reflectance. The data of all the SACURA SCIAMACHY retrievals for years 2002–2006 are available at www.iup.physik.uni-bremen.de/sacura. The correspondent cloud retrieval algorithm is described by the study in [7].

The aim of this paper is to compare COT as derived from SCIAMACHY data with results obtained using other instruments on the ENVISAT platform. Collocated measurements of the Advanced Along Track Scanning Radiometer (AATSR) and the Medium Resolution Imaging Spectrometer (MERIS) are used for this purpose (see, e.g., http://www.esa.int/envisat/instruments.html for the detailed description of AATSR and MERIS). Similar results in the cloud retrieval from different instruments would support possible synergies of the different instruments to compensate some disadvantages of the particular instruments.

MERIS is a 68.5° field-of-view pushbroom imaging spectrometer that measures the solar radiation reflected by the Earth at a ground spatial resolution of 300 m, in 15 spectral bands, and programmable in width and position in the visible and near infrared. MERIS allows global coverage of the Earth in three days. The reduced resolution mode (RRM) of MERIS used in this paper has a spatial resolution of 1040 m across track and 1160 m along track. Therefore, the resolution of MERIS is better than SCIAMACHY because there are about 2000 individual MERIS retrievals for one analyzed SCIAMACHY ground pixel. An RRM scene of MERIS consists of 1121 × 1121 pixels and covers 1165 (across track) × 1300 km (along track). The spectral measurement is different from SCIAMACHY. Measurements are performed at wavelengths 412.5, 442.5, 490, 510, 560, 620, 665, 681.3, 708.8, 753.8, 760.6, 778.8, 865, 885, and 900 nm [1]. Due to the spectral neutrality of the cloud reflectance, just one wavelength (442.5 nm) is used in SACURA as applied to MERIS. The ground reflectance is low at this wavelength and can be safely ignored for the case of optically thick clouds considered in this paper.

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As far as AATSR is concerned, it is a sensitive and precise imaging radiometer with several important and innovative technological features, which lead to exceptional levels of performance [16]. This includes the following.

1) A sophisticated onboard calibration system for its three thermal channels, viewing two black bodies every scan. For the four visible and reflected infrared channels, AATSR views a sample of the solar radiation from a diffuser plate once per orbit.
2) Stirling cycle mechanical coolers that maintain the thermal detectors at their optimum operating temperature close to 100 K.
3) A dual-angle view, whereby the same terrestrial scene is viewed at two different angles, one close to nadir and the other at 53°–56° to nadir (0°–22°). The dual-angle view is the most important and the defining feature of all the ATSRs. It means that each part of the Earth's surface over flown by sensor is viewed through two different atmospheric path-lengths and hence leads to a more precise atmospheric correction for sea surface temperature estimation, as compared to conventional multichannel sensors currently in operational use.

Predecessors of AATSR were ATSR-1 and -2. ATSR-1 measured in the infrared at 1.6, 3.7, 11, and 12.0 μm and had no visible channels. ATSR-2 and AATSR include the same four infrared channels of ATSR-1 and three additional channels at 0.55, 0.67, and 0.87 μm. AATSR is similar to ATSR-2, but components have been redesigned to match the new platform environment of ENVISAT. The details of the scan and calibration systems, spatial resolution, and swath have been kept as close as possible to the earlier instruments to ensure data continuity. The major advantage of AATSR over ATSR-2 can be seen in the data downlink. While ATSR-2 had restrictions on the amount of downlinked data due to platform constraints which particularly affected the visible channels, AATSR can send down data from all channels continuously at full 12-bit radiometric resolution. This also simplifies the data processing for AATSR since the processor does not have to cope with the wide range of instrument data formats used for ATSR-2.

MERIS cloud retrievals are available online (http://envisat.esa.int/instruments/meris/data-app/dataprod.html#level2). This is not the case for AATSR at the moment. Therefore, we have retrieved COT from AATSR data using the two-channel (550 and 1600 nm) algorithm SACURA [7] and compared both the AATSR and MERIS results with SCIAMACHY COT retrievals available at www.iup.physik.uni-bremen.de/sacura. The results are shown in the next section. In addition, COT and other cloud optical characteristics, as retrieved by SCIAMACHY, are compared to retrievals using the Moderate Resolution Imaging Spectroradiometer (MODIS) flying onboard the Terra satellite. MODIS has 36 channels in the range of 0.4–14 μm, with a channel-dependent spatial resolution [3] and a scan width of 2300 km. For this paper, 1-km^2 resolution data of MODIS on Terra at 550 and 1600 nm have been used.

II. Comparison of Cloud Retrievals

The extended cloud field covering central Europe on May 12, 2004 is shown in Fig. 1. This field has been used for the intercomparison of various satellite instruments in the retrieval of cloud properties. Only completely cloudy pixels have been analyzed. The location of the AATSR, MERIS, and MODIS ground scenes used for the comparison with SCIAMACHY measurements is shown in Fig. 1 [a Spinning Enhanced Visible and Infrared Imager (SEVIRI) Meteosat-8 image]. In particular, the region in the vicinity of the point (16.49 E, 53.96 N) has been used for the comparison with MODIS onboard Terra. The region located at 52–54 N, 8–13 E have been used for the comparison with MERIS, and the region with coordinates 55.4–57.1 N, 8–15 E (see Fig. 2) was used for the comparison with AATSR retrievals. The difference in locations is due to the fact that it is difficult to select a scene where all instruments measure simultaneously. Note that MODIS measurements have been performed with a 30-min delay as compared to those of SCIAMACHY. However, the atmospheric situation was very stable at this date, which is confirmed by the Meteosat-8 observations. Therefore, we do not expect great differences in the properties of clouds on the scale of 30 min. The measurements by SCIAMACHY, MERIS, and AATSR have been obtained at the same time, and the data have been provided by the European Space Agency (orbit 11499 of ENVISAT, 10 : 00 UTC,

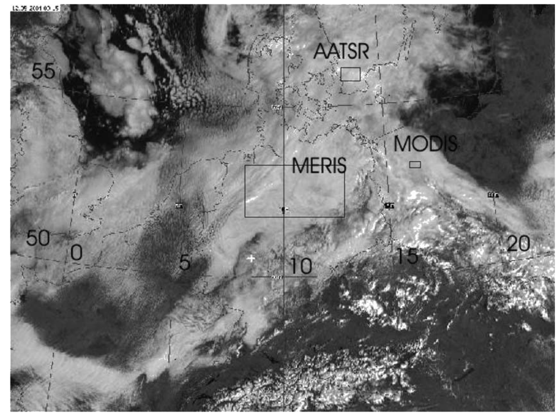

Fig. 1. Browse image of the extended cloud field obtained using SEVIRI/Meteosat-8 (May 12, 2004). The regions for the intercomparison are identified by the boxes and the name of the instrument.

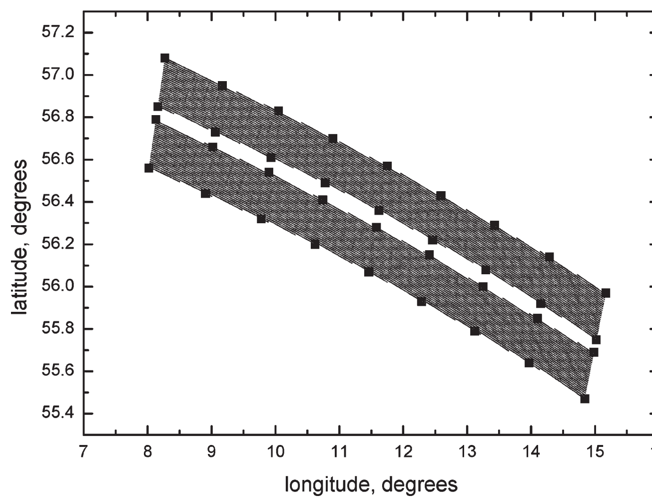

Fig. 2. Position of selected pixels of SCIAMACHY (see 16 rectangular areas indicated by black boxes in the corners). AATSR pixels are inside SCIAMACHY large pixels (gray areas).

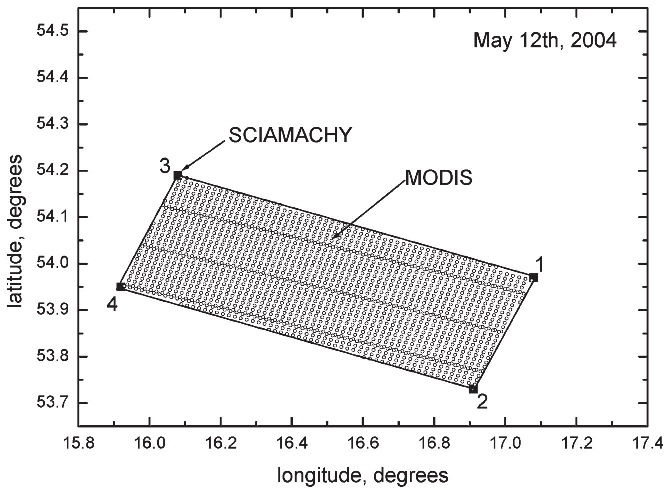

Fig. 3. Position of selected MODIS pixels inside a single SCIAMACHY 30×60 km^2 pixel.

May 12, 2004). MODIS data for roughly the same time period (10 : 26 UTC, May 12, 2004) have been obtained from Marburg Satellite Station (Germany).

An important question is the selection of MERIS, MODIS, and AATSR pixels inside the larger SCIAMACHY ground scene of 30×60 km^2. Simple geometrical calculations show that only pixels with coordinates $x \in [m, n]$ and $y \in [p, q]$ (see Fig. 2), where the vector parameter $\vec{\Upsilon}(m, n, p, q)$ is defined below, should be considered in the retrieval procedure. For instance, a MODIS pixel with the center located at the point $A(x, y)$ will fall inside the required rectangular area (see Fig. 3), if $m < x < n$ and $p < y < q$ with (m, n) determined by y via (1) and (p, q) determined by x via (2)

$$m = x_3 + \frac{(x_3 - x_4)(y - y_3)}{y_3 - y_4} \qquad n = x_1 + \frac{(x_2 - x_1)(y - y_1)}{y_2 - y_1} \tag{1}$$

$$p = y_2 + \frac{(y_4 - y_2)(x - x_2)}{x_4 - x_2} \qquad q = y_1 + \frac{y_3 - y_1}{x_3 - x_1}(x - x_1). \tag{2}$$

Here, the pair (x_j, y_j) with $j = 1, 2, 3, 4$ gives the position of SCIAMACHY edge points, as shown in Fig. 3. The accuracy of the selection technique is demonstrated for 16 SCIAMACHY pixels of 30×60 km^2 in Fig. 2 for the comparisons with AATSR and for one SCIAMACHY pixel in Fig. 3 for the comparisons with MODIS.

The results of retrievals using MERIS measurements at a wavelength of 443 nm for the entire area under study are shown in Fig. 4. The version of SACURA, as described by Kokhanovsky and von Hoyningen-Huene [5], has been used for the MERIS retrievals. The analysis of SCIAMACHY cloud phase index (CPI) for the area confirms that we deal with water clouds in the case studied. The correspondent SCIAMACHY CPI map for May 12, 2004 can be downloaded from the SACURA web site listed above. Unlike the standard SACURA version, the SACURA MERIS version does not require information on the size of particles in the retrieval of COT τ. It is assumed that droplets have an effective radius (ER) 6 μm with the gamma droplet size distribution and a coefficient

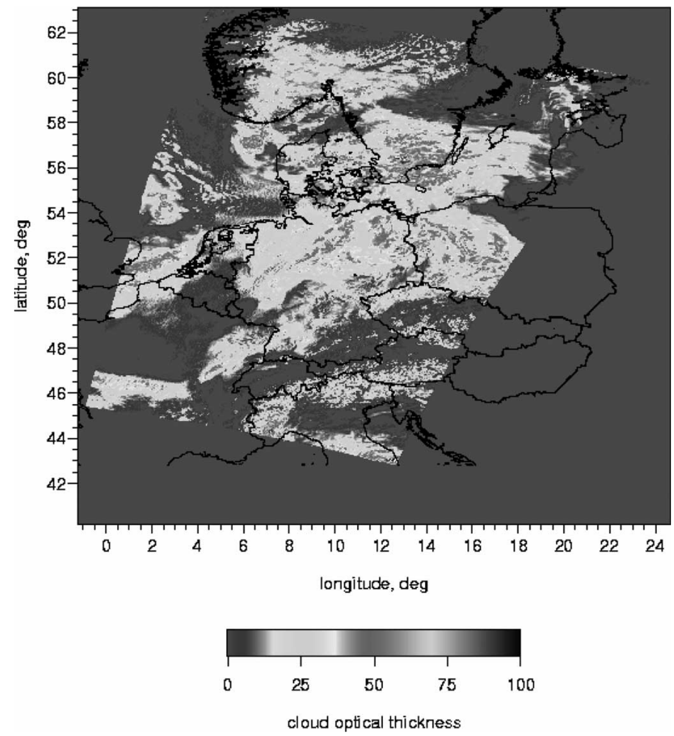

Fig. 4. COT map as derived from MERIS observations at a wavelength of 443 nm using SACURA.

of variance equal to 37%. An *a priori* assumption on the size of droplets makes additional errors in the MERIS-derived COT because the retrieval is (weakly) sensitive to the assumed value of the ER. Actually, the satellite-derived value of the transport optical thickness $\tau_{\rm tr} = (1 - g)\tau$ is almost insensitive to the assumed value of the ER [5]. Therefore, the sensitivity to the size of particles is mostly due to the dependence of the asymmetry parameter g on the size of particles. Because g increases with the size of particles, the assumption of $a_{\rm ef} = 6$ μm will underestimate COT $\tau = (1 - g)^{-1}\tau_{\rm tr}$ if in reality the size of the particles is larger than 6 μm. Our estimations give the bias in a COT of 10% at the wavelength of 413 nm, if in reality the ER is 20 and not 6 μm. Unfortunately, MERIS does not perform measurements at 1640 nm, which could make the retrieval of $a_{\rm ef}$ possible. The correspondent channel must be added in the next version of this instrument.

The calibration of SCIAMACHY reflectances has been performed as explained in [9] prior to the retrievals. In particular, the SCIAMACHY reflectances at 443 and 1550 nm have been multiplied by 1.07 and 1.15, respectively.

It follows from the analysis of the retrievals shown in Fig. 5 that clouds are quite thick with values of COT in the range 20–50 for most of the cases. The comparison of retrievals with collocated SCIAMACHY measurements at the same wavelength is shown in Fig. 5. Only completely cloudy homogeneous scenes were used in the analysis, with the cloud fraction being derived from MERIS data having 1-km^2 spatial resolution. There were around 1800 MERIS pixels in one large SCIAMACHY pixel.

The black squares in Fig. 5 represent the results as extracted from the data shown in Fig. 4 for the region indicated in Fig. 1 (52–54 N, 8–13 E). Circles have been obtained

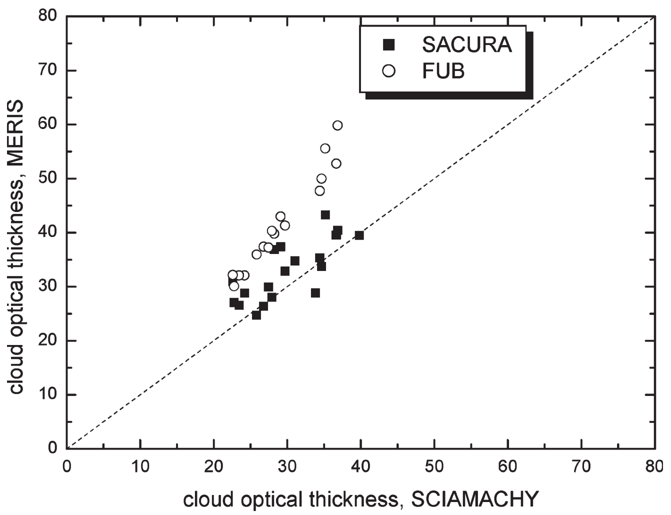

Fig. 5. Intercomparison of COT at 443 nm, derived from SCIAMACHY and MERIS for the region 52–54 N, 8–13 E shown in Fig. 1. SACURA was applied to both MERIS and SCIAMACHY data. FUB algorithm was applied only to the MERIS data.

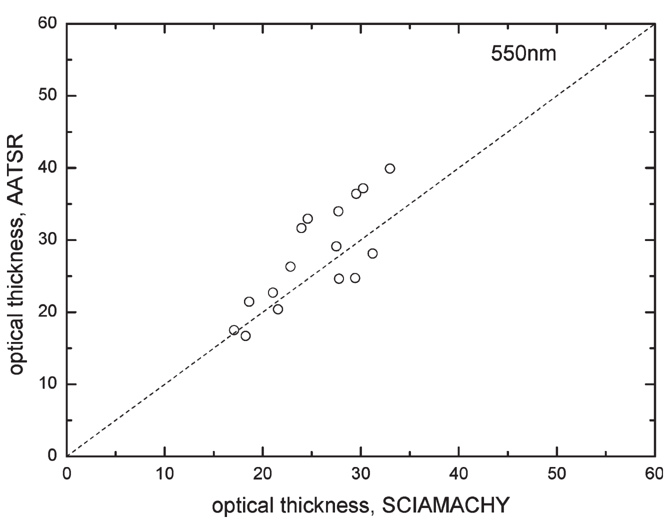

Fig. 6. Intercomparison of COT at 550 nm, derived from SCIAMACHY and AATSR using SACURA for the 16 SCIAMACHY pixels shown in Fig. 2.

using the operational MERIS cloud retrieval algorithm. The algorithm has been developed at the Free University of Berlin (FUB) [see Algorithm Theoretical Basis Document (ATBD) at http://www.brockmann-consult.de/mapp/ATBD_Pdf/07_MAPP-ATBD-CACOT.pdf].

First of all, we see that SCIAMACHY is capable of determining COT needed in the gaseous retrievals. For instance, retrievals using the SACURA and MERIS or SCIAMACHY data give very similar results. The FUB algorithm, as applied to the MERIS data, gives systematically larger values as compared to the SACURA MERIS retrievals, which can be related to different methodologies and *a priori* assumptions followed in FUB and SACURA cloud retrievals.

The comparison with AATSR measurements is given in Fig. 6 for homogeneous completely cloudy pixels at the location shown in Fig. 1. Again, we see that SACURA, as applied to SCIAMACHY, retrieves COT in a good correspondence

TABLE I
CLOUD PARAMETERS RETRIEVED USING SACURA AS APPLIED TO SCIAMACHY AND MODIS. THE CENTER OF THE SCIAMACHY PIXEL IS LOCATED AT (16.49 E, 53.96 N). CORNERS ARE LOCATED AT THE FOLLOWING POSITIONS (SEE FIG. 3): 1—(17.08 E, 53.97 N), 2—(16.91 E, 53.73 N), 3—(16.08 E, 54.19 N), AND 4—(15.92 E, 53.95 N)

Instrument	ER, μm	LWP, g/m^2	COT	CTH, km
SCIAMACHY	10.08	87.26	13.51	3.30
MODIS	9.7	102.38	16.65	2.76
Difference	**+0.38**	**-15.12**	**-3.14**	**+0.54**

TABLE II
STATISTICAL CHARACTERISTICS OF A CLOUD (AS DERIVED FROM MODIS) AND RELATIVE DIFFERENCES FOR THE DATA SHOWN IN TABLE I

Parameter	ER, μm	LWP, g/m^2	COT	CTH, km
Standard deviation, μm	1.55	39.74	5.59	0.36
Coefficient of variance, %	16.0	38.82	33.57	13.04
Relative difference, %	+3.92	-14.77	-18.86	+19.56

with the data obtained from the SACURA AATSR retrievals. The results obtained are encouraging. Indeed, we see that measurements by all three instruments lead to very similar results for COT. This also means that the synergy between these instruments can be further explored and used in studies of various atmospheric and surface parameters.

We also have compared the SCIAMACHY COT retrievals with the results obtained from MODIS measurements using SACURA. This is summarized in Tables I and II for the SCIAMACHY pixel with the center located at the point (16.49 E, 53.96 N). Just one SCIAMACHY pixel containing around 1800 MODIS pixels was analyzed. In addition to COT, the ER of droplets, liquid water path (LWP), and cloud top height (CTH) are also compared. It follows that ER differs by just 0.4 μm from the MODIS result. Such a small deviation is partially due to the fact that the cloud was very uniform (with respect to ER) with a standard deviation of ER of just 1.55 μm (see Table II). The difference in COT is equal to 3.14, which gives an underestimation of about 19% for SCIAMACHY. This underestimation can be explained by the fact that the coefficient of variance of MODIS COT was quite large (approximately 34%, see Table II). Theoretical considerations [4] lead to the conclusion that larger pixels give smaller reflectances as compared to the average value of the reflectances for smaller pixels falling inside a single large pixel (see Fig. 3) in the case of horizontally inhomogeneous clouds. Therefore, the discrepancy found can be partially related due to the differences in the size of pixels. LWP is also underestimated by SCIAMACHY but with a somewhat smaller relative difference as compared to COT (see Table II as derived from the MODIS data). The difference in the CTH is approximately 0.5 km, which

corresponds well to similar differences of CTHs obtained from comparisons between the SCIAMACHY and Global Ozone Monitoring Instrument (GOME) oxygen A-band-derived CTHs with corresponding radar and thermal IR CTH measurements [6], [13], [14]. This difference may be explained by the underestimation of low cloud altitudes by MODIS, which is a typical feature of many IR instruments [15], but it could also be caused by uncertainties related to the simplifications incorporated in the SACURA forward model (e.g., vertically homogeneous cloud layers, etc. [12]). The retrievals of COT, ER, and LWP have been performed using a SACURA version designed specifically for MODIS retrievals [10]. CTH was determined using satellite measurements at 12 μm in conjunction with a temperature profile measured nearby at the Lindenberg observatory. A black body assumption was made in the retrieval of CTH.

NASA lookup table (LUT) technique [11], as applied to MODIS data, gives the results very similar to those reported in Table I, which are obtained with SACURA. Note that NASA technique also uses the asymptotic theory in the part of retrievals related to optically thick clouds.

Histograms of MODIS-retrieved ER and COT are shown in Fig. 7(a) and (b). We found that average ER, COT, and LWP derived using NASA LUT approach were 9.91 μm, 15.29, and 100.64 g/m^2, respectively. This differs by just 0.21 μm (ER), 1.36 (COT), and 1.74 g/m^2 (LWP) from results obtained using SACURA as applied to the MODIS data (see Table I). This suggests that SACURA has a high accuracy. The small differences can be explained partially by the fact that SACURA and NASA LUT techniques are based on different *a priori* assumptions (e.g., the type of the cloud droplet size distribution, etc.) and partially due to the fact that SACURA is valid only for clouds with COT larger than 5.

CTH as derived by the standard MODIS retrieval algorithm was approximately 752 hPa for the SCIAMACHY pixel, which roughly corresponds to 2.5 km. This differs by 0.8 km from the result derived from SCIAMACHY measurements (see Table I) using spectral measurements in O_2-A band and by 0.26 km from our estimation of CTH using MODIS IR measurements combined with a temperature profile measured at the Lindenberg Observatory (see Table I). The reason for this difference could be not only errors of SACURA but also underestimation of CTH by IR imagery for the case of low clouds.

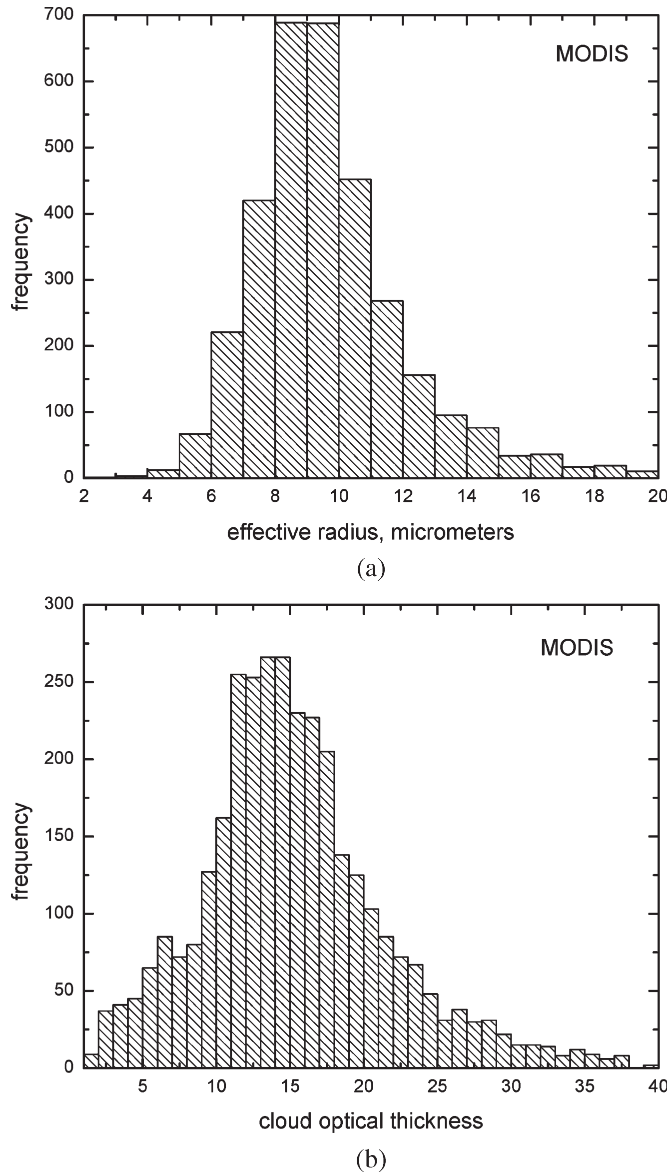

Fig. 7. Frequency distribution of the NASA LUT MODIS-retrieved values of (a) ER and (b) COT for the SCIAMACHY 30 $\times$ 60 km^2 pixel shown in Fig. 3.

III. Conclusion

We have retrieved COT using SACURA as applied to multiple optical instruments observing the same cloud field on May 12, 2004 around 10:00 UTC. It was found that all instruments give coherent results. This fact is encouraging and confirms a good performance of correspondent satellite instrumentation. Some differences discovered in SACURA and the FUB MERIS algorithm can be explained by the different settings of these techniques (e.g., with respect to the assumed size of particles). As one might expect, the differences increase with COT (see Fig. 5) due to the general loss of sensitivity of measurements to COT for thicker clouds.

The comparisons involving averages of about 1800 MODIS 1-km^2 pixels (see Fig. 3) show that SCIAMACHY gives results similar to that of MODIS. Further studies on larger statistical databases are needed to confirm this result.

The calibration error of SCIAMACHY data with the Processor 5.01 used in this paper is about 10% (underestimation) in the visible and near IR [9]. Therefore, SCIAMACHY radiances were multiplied by 1.07 for the wavelength of 443 nm and 1.15 for the wavelength of 1.55 μm prior to the retrievals to account for the results of the SCIAMACHY vicarious radiometric calibration, as reported [9].

The results shown above confirm that studies of atmospheric parameters based on the synergy of multiple optical instruments currently in space are feasible.

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